COMPOSITIONAL GRADIENTS ACROSS MARE-HIGHLAND CONTACTS: THE IMPORTANCE OF LATERAL MIXING. Lin Li, J.F. Mustard and G. He, Department of Geological Sciences, Box 1846, Brown University, Providence RI 02912. (li@geo.brown.edu)

Introduction: The relative importance of vertical vs. lateral mass transport on the Moon has been the object of much debate [1,2,3,4,5,6,7]. With the new multispectral observations provided by the Clementine spacecraft, we can now quantitatively analyze the magnitude of transport and assess the processes contributing to the observed distributions. We are currently analyzing a number of mare-highland boundaries (e.g. Grimaldi, Tsiolkovoskiy, and Frigoris) but most analyzed thus far exhibit similar systematics to that observed in the Grimaldi Basin [8]. On the basis of these results of observation, we seek to interpret and model the observed variation of mare/highland abundance through the use of a mathematical model that can quantitatively reproduce spatial distributions and the absolute concentrations of "exotic" components on the mare or highland side.

In previous analysis [8], we used a linear spectral mixing model to compute abundance information [9]. In this analysis, however, we use a nonlinear model, which is more accurate for the intimate mixing expected in lunar surface [9]. On the basis of nonlinear spectral mixing analysis, two critical issues are clarified: 1) There are apparently two distinct mixing zones: a) near the contact that is very steep (5-15%/km) and b) far from the contact that is very gentle (<2%/km). 2) The distribution of mare and highland across the contact is remarkably symmetric. The abundance of mare and highland are equal to 50% at the geologic contact and the amount of mare transported to the highland is approximately equal to the amount of highland to the mare. This remarkable symmetry indicates that deep vertical transport is unimportant relative to lateral transport.

Since lateral transport and mixing of mare and highland is likely responsible for the formation of compositional gradients across simple boundaries of mare and highland, it is required that the mathematical model not only reproduce the observed variation of mare abundance, but also can be related to the geological process that created the variations.

Model Description: There have been many studies of regolith dynamics where the evolution of surface composition and maturity have been related to the impact process [10,11,12,13,14,15]. It is generally assumed that meteoritic bombardment of the lunar surface is a random processes governed by the size-frequency distribution of the impact population. Because the gradient of mare abundance is symmetric across the geological contact, it is predicted that the ejecta of both mare and highland has the same probability of emplacement across the contact, and that the topographic contrast between mare and highland has little effect on the mixing process [15]. Other assumptions about the meteoritic flux, mass and speed distribution, and cratering process are the same as those described by [16].

Diffusion is a process that occurs when there is a net transfer of material from both sides of a compositional boundary. Classical diffusion results from molecular motions where the motion of each molecule is random and independent. Although it is not possible to specify the path any particular molecule will move in a given interval of time, on the average there is a net transfer across the boundary [17]. We propose therefore that over time the transfer of mare or highland ejecta across a contact is a random process driven by impact cratering. In this way, the distribution of mare and highland can be modelled by diffusion equations. The basic formulation [17,18] is

$$\frac{\partial C}{\partial t} = D\frac{\partial C^2}{\partial x^2} \qquad (1)$$

From which the solution is derived.

$$C = \frac{C_0}{2} \times erfc(\frac{x}{2\sqrt{Dt}})$$

C is the mare abundance, D is diffusion coefficient, x is distance, t is time. For an initial condition, C is assumed to be 100% on the mare side, and on the highland side 0%. Furthermore, the mare abundance is defined to be 100% on the mare side and 0% on the highland side when x is large relative to the width of mixing zones.

Result and Discussion: Three profiles of mare abundance across the mare-highland boundary on the southern end of Grimaldi (Fig.1) were produced using the mare fraction image of nonlinear spectral mixing analysis. It is evident in Fig.1 that there are two mixing zones in the mixing profiles and the profiles are symmetric about the contact. We substitute the Grimaldi age [19] of 35 time units (unit time:10^8 years) and diffusion coefficient D=0.1 into the solution of differential equation (1), we get the simulated mare abundance profiles presented in Fig.2. It is apparent that the simulated curves only fit the steep mixing zone of mare abundance profile, can not reproduce the moderate mixing zone. Thus, a modified equation (2) with two diffusion coefficients D1 = 0.025 and D2 = 5.5 is appealed to model the profiles:

$$\frac{\partial C}{\partial t} = D_1\frac{\partial {C_1}^2}{\partial x^2} + D_2\frac{\partial {C_2}^2}{\partial x^2} \qquad (2)$$

$$C = \frac{C_0}{4} \times \{erfc(\frac{x}{2\sqrt{D_1 t}}) + erfc(\frac{x}{2\sqrt{D_2 t}})\}$$

The result is shown in Fig.3 The simulated curves in Fig.3 can fit both the steep mixing zone and the moderate mixing zone. We plan to conduct inverse modelling of the profiles to better determine the diffusion coefficient.

Dimensional analysis of the diffusion coefficient in the context of impact cratering indicates that the

Compositional gradients on the Moon...Mustard, Li, and He

different diffusion coefficients should be related to a definite range of crater diameters. The large craters should transport ejecta greater distance than small craters, and therefore have larger D. In addition, discontinuous ejecta facies may have a larger D than continuous ejecta. However, small impacts are more frequent and therefore may have effectively larger D per unit time. The fact that equation (1) can model the steep mixing zone supports our previous conclusion that the production of mare - highland compositional gradients is the result of simple lateral mass transport of surface materials due to the time-averaged effects of impact cratering and regolith gardening [8,20]. However, we require two diffusion coefficient to model both steep and shallow mixing gradient, suggesting that there are at least two superimposed prosesses at work. That equation (2) can model both mixing zones implies that the discontinuous ejecta facies of larger scale cratering govern the formation of shallow mixing zone. In previous analyse [8], we attributed the formation of moderate mixing zones to some far-field effect that might be from the discontinuous ejecta facies. The results shown in Fig.3 further verify our conclusion.

We have considered an alternative process whereby large craters provide the diffusion sources in select unit time interval, and then independent smaller craters "diffuse" the ejecta produced by larger craters [12]. If this were the case, we could model the boundaries through an equation with a single D. However, the mare abundance at the interface of steep and moderate mixing zones can not be satisfied by a solution of this kind of the equation. So, we conclude that the formation of moderate mixing zones is not due to continuous ejecta only, but requires a componenet of discontinuous ejecta.

Reference: [1] Rhodes, J.M., et al., *Philos. Trans. R.Soc. London* A, 285:293-301, 1977. [2] Horz, F., *Proc. Lunar. Planet. Sci. Conf. 9th*, 3311-3331, 1978. [3] Farrand, W., et al., *Proc. Lunar. Planet .Sci. Conf.18th*, 319-329, 1988. [4] Simon, S.B., et al, *Proc. Lunar. Planet . Sci. Conf. 20th*, 219-230, 1990. [5] Oberbeck, V.R., et al., *Rev. Geophys*., 13:337-362, 1975. [6] Pieters, C.M., et al., *JGR* 90:12393-12413, 1985. [7] Fischer, E.M., et al., *JGR* 100:23279-23290. [8] Li L., et al., *LPSC XXVI* 751-752, 1996. [9] Mustard, J.F., et al., *LPSC XXVIII*, this volume. [10] Gault, D.E., et al., *Proc. 5th Lunar. Sci. Conf*. 3:2365-86, 1974. [11] Oberbeck, V.R., et al., Icarus 19:87-107, 1973. [12] Quaide, W.L., et al., *Moon* 13:27-55, 1975. [13] Arnold, J.R., *Moon*. 8:35-24,1975a. [14] Arnold, J.R., *Proc. 6th Lunar Sci .Conf.*, 2:2375-2395, 1975b. [15] Mustard, J.F.*JGR*,101,18913-25, 1996. [16] Langevin, Y., *Ann. Rev. Earth Planet. Sci*, .5:449-89, 1977. [17] Crank, J., *The Mathematics of Diffusion, Clarendon Press.Oxford*, 1975. [18] Genther, R., et al., *Partial Differential Equations of Mathematical Physics and Integral Equations, Dover Publications, INC. New York*, 1996. [19] Williams, D.A., et al , *JGR* 100: 23291-23299, 1995. [20] Arvidon, R.E., et al.,*Moon*. 13:67-79, 1975.

Support from NASA Grants NAGW-3379 and NAGW-4896 is gratefully acknowledged.

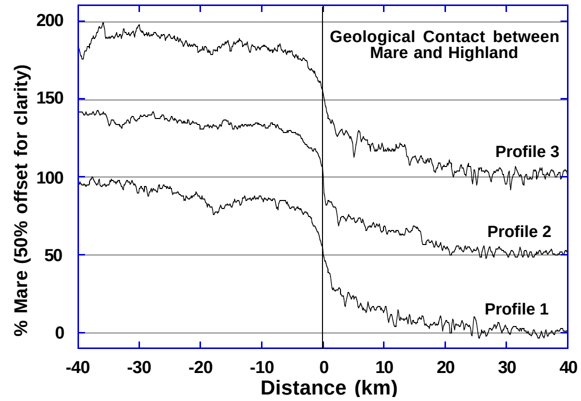

Figure 1. Profiles of mare abundance across the Grimaldi mare-highland geologic contact.

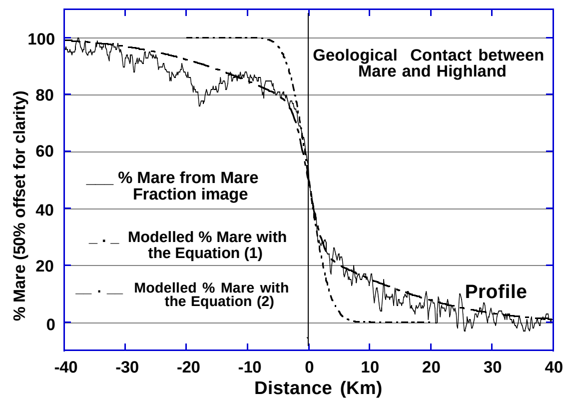

Figure 2. Comparison between % mare modelled with equation (1) and (2)

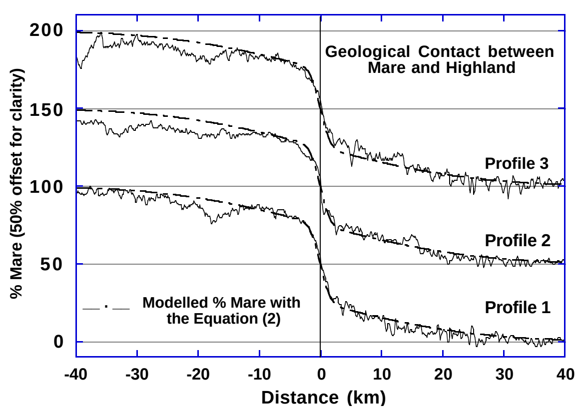

Figure 3. Comparison between % mare of three profiles and modelled with equation (2).